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Modeling Atmospheric Scatterers Using Spacecraft Observations

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During this year research has focused on modeling Uranus' secular variability and on preparing to analyze data from the Galileo Probe Nephelometer experiment.

During the past 20 years, Uranus' brightness has varied by about 4% in blue light (wavelength 0.472±0.021 μm) and about 11% in yellow (0.551±0.023 μm) (Lockwood *et al.* 1985; Lockwood, private communication). About 2% of the variation at both wavelengths can be attributed to the change in the area of Uranus' apparent disk as our point of view shifted from about 30°S in 1972 to nearly pole-on in 1986, but the remainder is due to intrinsic brightness changes in the planet's atmosphere.

Uranus appears basically featureless upon casual inspection, but closer examination reveals subtle latitudinal bands which vary in brightness by ~5% (Smith *et al.* 1986). Scattering models for seven latitude bands in the southern hemisphere have been developed which reproduce the Voyager imaging observations throughout the near encounter, covering a range of solar phase angles from 14° to 158°. This is shown for one Voyager filter in Figure 1, where a longitudinal scan taken with the MeJ (0.619 μm) filter (heavy solid line) is compared with specific intensities predicited for the seven different latitude bands. As they should, the observations correspond most closely to the low-latitude models at low latitudes and to the high-latitude models at high latitudes, with a sharp transition at ~35°. When this latitudinal banding is included in the calculation of Uranus' disk brightness as seen from Earth since 1972, it can account for about half of the required intrinsic brightness change in blue, but only about 20% of the change seen in yellow. Therefore, the scattering properties of Uranus' atmosphere must have changed between 1972 and 1986, when the Voyager observations were made.

At the time of the Voyager encounter in 1986 Uranus had a methane cloud at a pressure of about 1.2–1.3 bars in its troposphere (Lindal *et al.* 1987), with an optical depth ranging from about unity at low latitudes to about 3 at high latitudes. Since Lockwood's yellow filter substantially overlaps the methane absorption band at 0.542 μm, and since the intrinsic brightness in yellow needs to drop between 1986 and 1972 by about five times as much as in the blue, an obvious possibility is that the optical depth of the methane cloud was much less in 1972, leading to greater absorption in the methane band.

Calculations reveal that reducing the methane cloud optical depth from its 1986 value causes the brightness in the blue filter to increase, while the brightness in yellow decreases by only about half the needed amount, even when the cloud optical depth is reduced to zero. This is shown in color-color diagram of Figure 2, where Lockwood's observations are represented by the open and filled circles, and the solid line shows how the yellow and blue magnitudes change as the methane cloud optical depth is reduced from its 1986 value (lower right) to zero (upper left). Further calcu-

Henyey-Greenstein phase functions have the form

$$P(\theta)=fP_{\mathrm{HG}}(g_1,\theta)+(1-f)P_{\mathrm{HG}}(g_2,\theta)$$

$$P_{\mathrm{HG}}(g,\theta)=\frac{1-g^2}{\left(1+g^2-2g\cos\theta\right)^{1.5}} \tag{1}$$

so there are four free parameters for in the equation for I/F — g_1, g_2, f, and the scattering optical depth τ_s (which must be <<1). It has the advantage of being very simple and quick to calculate, and of converging quickly on the best-fitting values of the free parameters for the Probe Nephelometer data set. It is widely used by people who only want phenomonologically reasonable particle scattering so they can investigate other things. It has the disadvantage of giving no direct information on the actual physical properties of the scatterers: particle size, number density, complex refractive index, etc.

This is where Mie theory comes in. It gives the exact solution for the single scattering phase function, single scattering albedo, and extinction efficiency for spherical scatterers of a given size and complex refractive index. Since the aerosols in the Jovian troposphere are most probably frozen ammonia, hydrazine, or photochemically produced hydrocarbons, there is no reason to expect them to be spherical. Therefore an empirical modification of Mie theory developed by Pollack and Cuzzi (1980) will be used. This modification can be described as follows:

For particle sizes less than some given value α_0, use Mie theory. For particle sizes greater than α_0, split the scattered light into diffracted, externally reflected, and internally transmitted components. Use standard formulae for diffracted and externally reflected components, and model the internally transmitted component as

$$T=\exp(a\theta^2+b\theta) \tag{3}$$

where a and b are calculated to produce a given slope s_0 at $\theta=0$ and a minimum at a given angle θ_{min}.

The model has a total of seven possible free parameters (which is two more than the number of available data points): the scattering optical depth τ_s, the complex index of refraction n_r-in_i (which counts as two parameters), the mean particle radius r_m, a parameter defining the width of the particle size distribution, and s_0 and θ_{min}. It may be possible to use continuity constraints between successive atmospheric layers to constrain the additional parameters.

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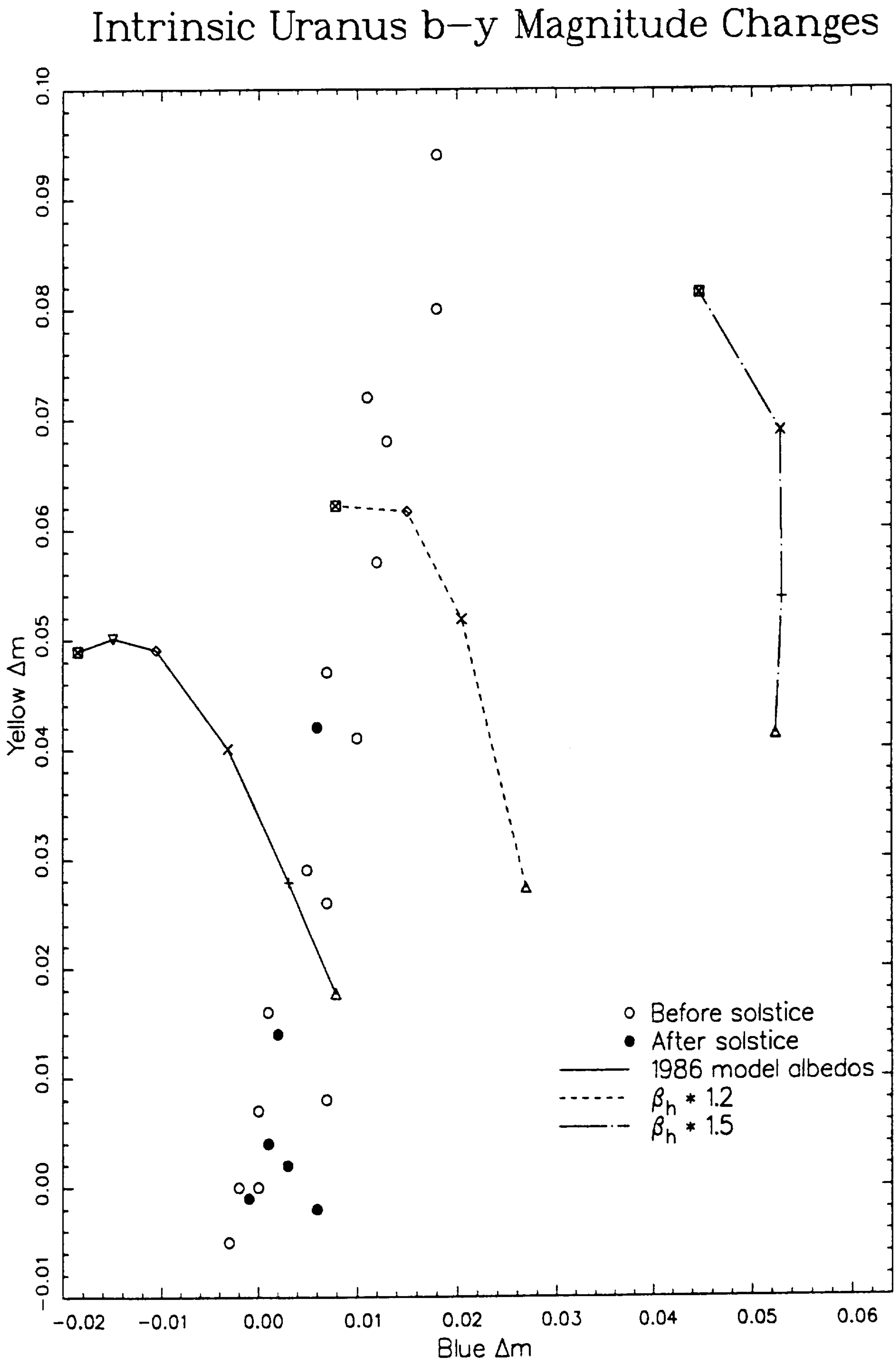
Intrinsic Uranus b−y Magnitude Changes
Yellow Δm
Blue Δm
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.01
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Before solstice
After solstice
1986 model albedos
βh * 1.2
βh * 1.5

Figure 2.